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Experimental evaluation of backfill around monopiles

Introduction:

Several foundation concepts for offshore wind turbines exists, cf. Figure 1. The choice of foundation depends among several factors on the sea and soil conditions. The monopile foundation concept, in which a pile made of welded steel is driven open-ended into the soil, is often employed. Typically, the pile diameter, *D*, is in the range of 4-6 m and the embedded pile length, *L*, around 20-25 m. Around monopiles installed in silty or sandy soil, erosion will take place. The waves and current can result in the forming of local scour around the monopiles. The depth of these scour holes can according to the design regulations, e.g. DNV (2004), be up to 1.3 times the pile diameter.

When designing monopiles situated in sandy or silty soil scour protection consisting of rock infill is often used. Scour protection is highly expensive and the most economic solution might therefore be to design the monopiles without scour protection and hereby allow the forming of scour holes. Due to changing sea conditions the depth of the scour hole will change over time. Hereby, also the total stiffness of the monopile foundation will be time dependent. Today the variation of the total stiffness of the foundation is not taken into account when designing the steel material in the pile for fatigue. Instead the depth of the scour hole is taken as a constant value corresponding to the maximum scour depth, resulting in a conservative design of the wall thickness of the monopile. In order to incorporate the variation of scour depth further research concerning the time scale of backfilling is needed in order to estimate the variation of the scour depth with time. Moreover, research is needed concerning the relative density, and hereby also the strength and deformation properties, of the backfilled soil material. In the present research the timescale of backfilling and the relative density of the backfilled soil material are assessed on the basis of experiments at the Large Wave Channel (GWK) of the Coastal Research Centre (FZK) in Hannover, Germany.

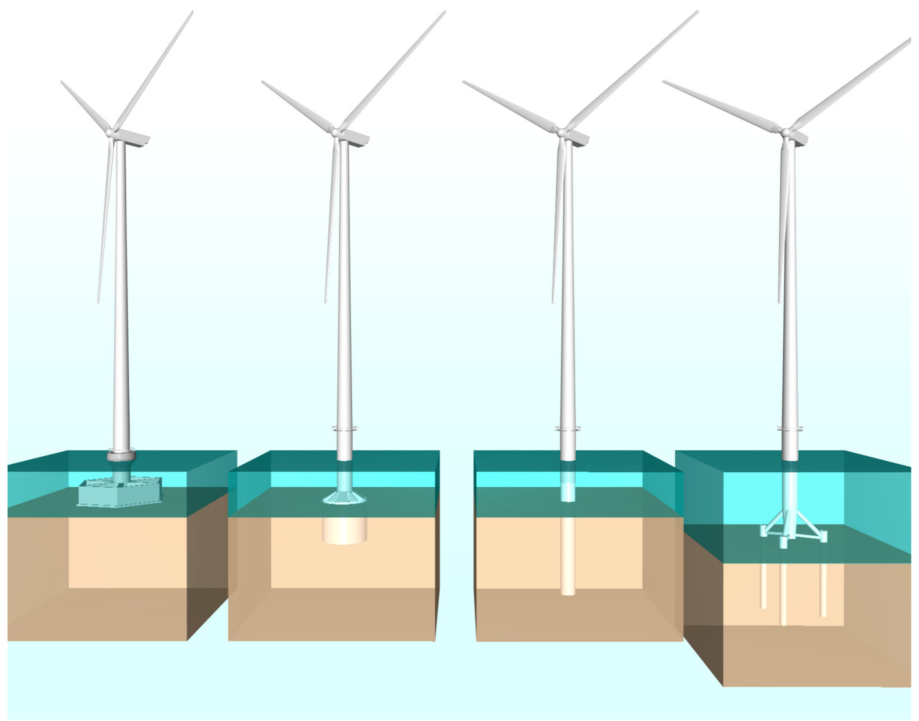

Figure 1: From the left: Graviational foundation, bucket foundation, monopile foundation, and tripod foundation.

Test setup:

Experimental tests of the time scale of backfill and of the relative density of backfilled sand material have been conducted at the Large Wave Channel (GWK) of the Coastal Research Centre (FZK) in Hannover, Germany. The length, width, and height of the wave channel are respectively, 324 m, 5 m, and 7 m. A piston-type wave generator with a capacity of 900 kW has been employed for the generation of waves. A cylindrical pile with an outer diameter of 0.55 m has been fixed to the bottom of the wave channel. Hereby the geometric scale between the model pile and the target field pile is in the range of 1:7-1:11. The pile was fixed in the centre of the wave channel. Near the pile well-sorted fine sand with a depth of 1 m was situated. The water level during the tests was 4 m above the bottom of the channel corresponding to a water depth of 3 m near the pile. In order to measure the wave parameters wave gauges were installed in several places along the length of the channel.

Test procedure:

- Manual preparation of scour hole, cf. Figure 2.
- Filling water into the wave channel, cf. Figure 3.
- Generation of waves. Continuous measurement of scour depth, cf. Figure 5.
- Drainage of water.
- Cone penetration tests and soil samples, cf. Figure 4.

Figure 2: Manually prepared scour hole.

Figure 3: Filling water into the wave channel.

Figure 4: Taking cone penetration tests of the soil after the generation of waves and drainage of water. The size of the scour hole after the waves can also be observed.

Figure 5: Running of waves and continuous measurement of scour depth.

Time scale of backfill

The scour depth of the scour hole was measured during the generation of waves as shown in Figure 5. The measured data was employed to estimate the time scale of backfill. According to Hartvig et al. (2010) the scour depth, *S*, at a given time can be estimated by:

$$S = S_\infty + (S_0 - S_\infty)\cdot\exp(-t/T)$$

where S_∞ is the equilibrium scour depth for the current sea condition, S_0 is the initial scour depth, t is the time, and T is the time scale. The variation of scour depth with time can be observed in Figure 6. Here it can be observed that a time scale of 10 min fits well with the measured data. The time scale can according to Sumer et al. (1993) be normalised as follows:

$$T' = \frac{\sqrt{g(s-1)d^3}}{D^2}T = 0.015$$

where *T'* is the normalised time scale, *g* is the acceleration due to gravity, *s* is the specific grain density, and *D* is the pile diameter. The normalised time scale is hereby *T'* = 0.015.

Hartvig et al. (2010) conducted small scale experiments on the backfilling process for a similar sea condition, e.g. *KC*, and θ of the same order. They found a normalised time scale of approximately 4.0. Hereby, it can be concluded that scaling effects, other than what is incorporated in the equation of normalised time scale, exists.

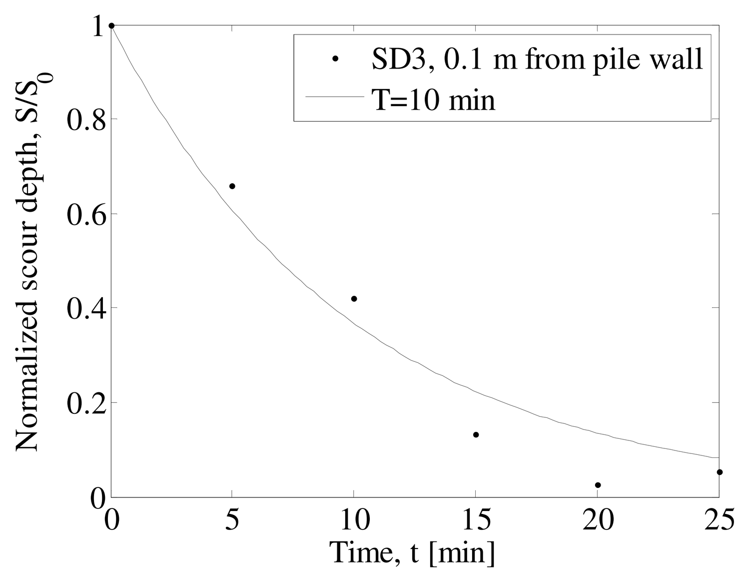

Figure 6: Variation of scour depth during the backfilling process.

Relative density of backfilled soil material

The relative density of the backfilled soil material has been determined based on both soil samples and cone penetration tests. A total of 5 soil samples and 2 cone penetration tests were conducted within the area of the original scour hole. The cone penetration tests has been interpreted as proposed by Ibsen et al. (2009). In Table 1 the relative density determined on the basis of the soil samples can be seen, and in Figure 7 the relative density determined on the basis of the cone penetration tests is shown. Near the soil surface relative densities of approximately 80 % has been found. Based on the cone penetration tests the relative density decreases with depth to a value of approximately 60 % at a depth of 400 mm.

Soil sample	Relative density, I_D
1	70 %
2	85 %
3	90 %
4	80 %
5	76 %

Table 1: Relative density of the backfilled soil material based on the taken soil samples.

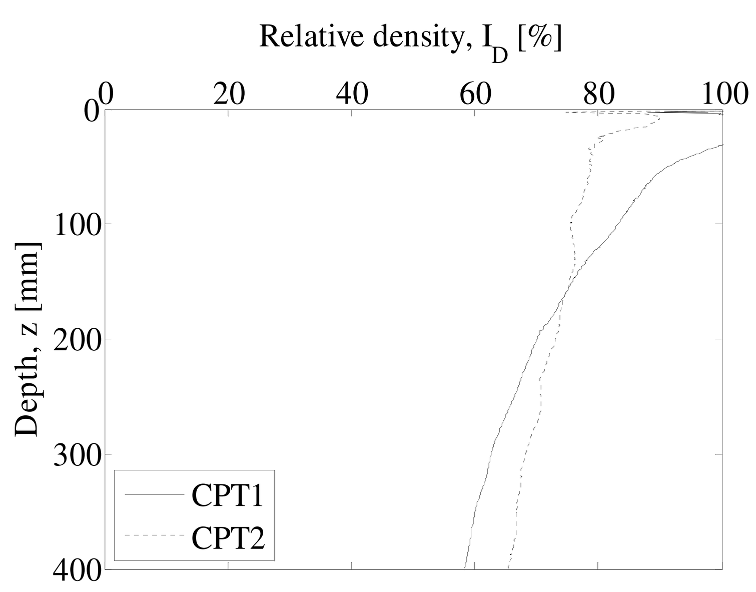

Figure 7: Relative density of the backfilled soil material based on the cone penetration tests.

Conclusion:

The major conclusions that can be drawn from the experiments at the Large Wave Channel (GWK) of the Coastal Research Centre (FZK) in Hannover are:

- Compared to the studies of Hartvig et al. (2010) the normalized time scale was found to be a factor of approximately 250 smaller although the Keulegan-Carpenter number and Shields parameter were in the same order for the two studies.
- From soil samples and CPT-measurements the relative density of the backfilled soil deposit was found to be approximately 80 % near the surface. Near the bottom of the original scour hole, the relative density was determined to approximately 60 %.
- As the backfilled soil deposit can be expected to be rather dense, the total stiffness of the foundation can be expected to increase by a large amount when the sea conditions changes from current dominated to wave dominated. If accounting for the variation of the total stiffness of the foundation in the fatigue limit state, large savings in the amount of steel used for the monopile might therefore be the result.

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